Synthesis, Characterization and Modeling of the Mn+1AXn Layered Ternary Carbides and Nitrides

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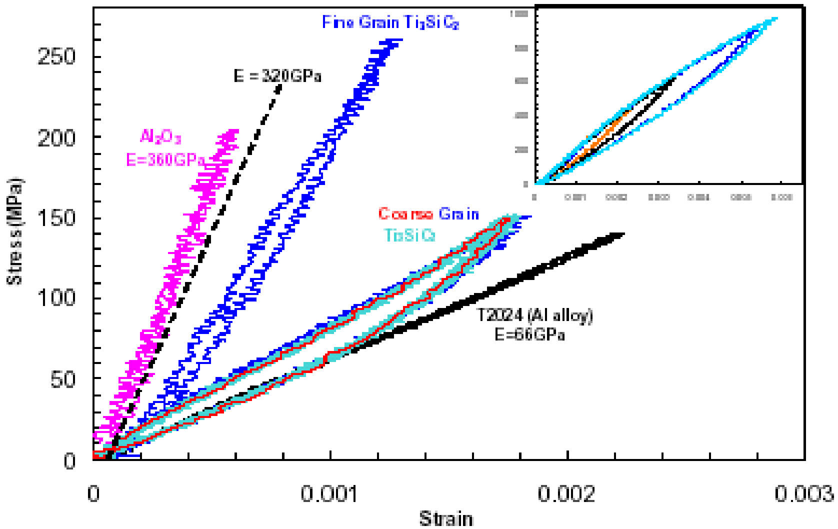

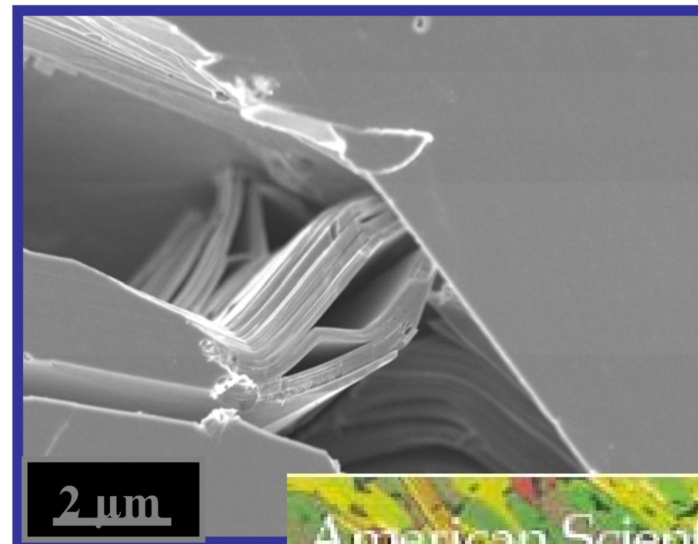

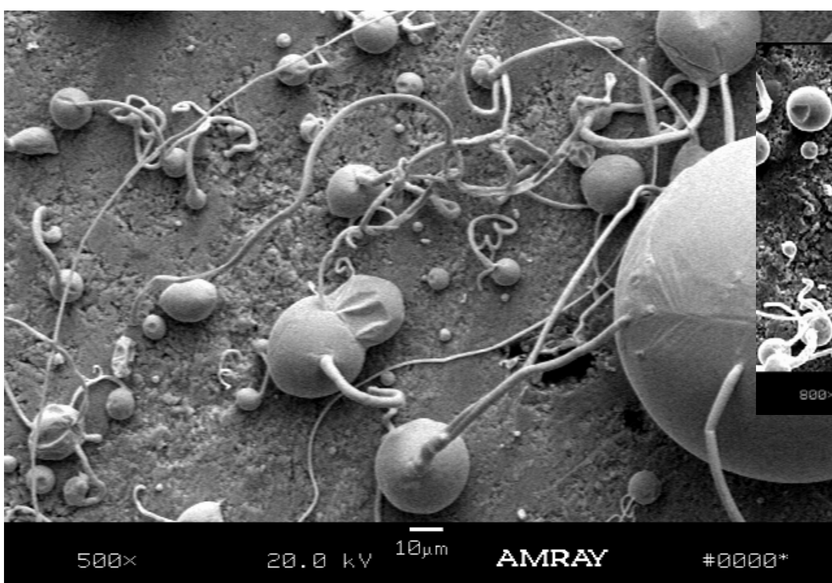

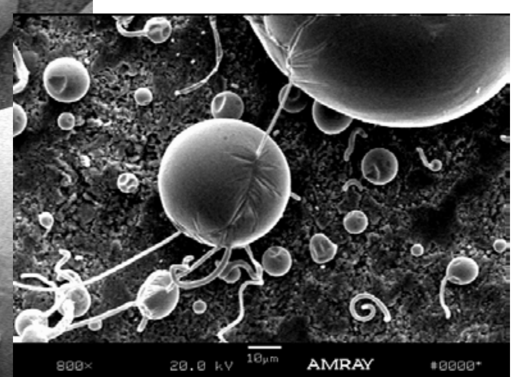

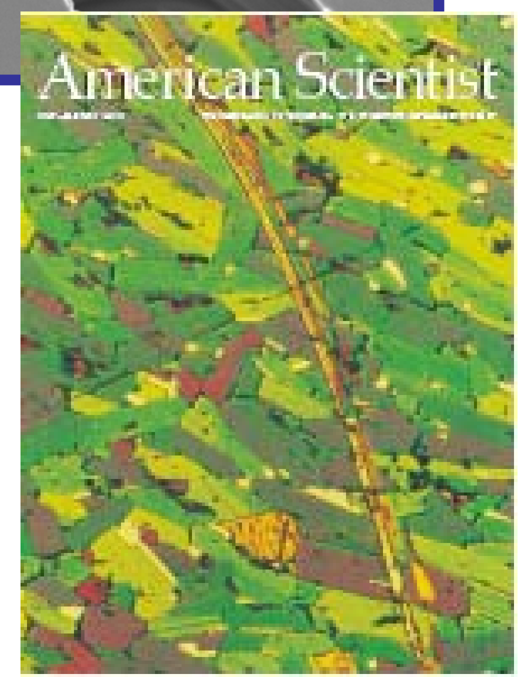

Top Left: It is a truth universally acknowledged that dislocation-based crystal plasticity is irreversible; it is also universally acknowledged that the stiffness of a solid is a weak function of microstructure in general, and grain size in particular. Here we show that these truths do not apply to a new class of layered ternary carbides and nitrides – the so-called MAX phases - of which Ti_3SiC_2 is a member. Macroscopic polycrystalline Ti_3SiC_2 cylinders can be compressed, at room temperature, to stresses of up to 1 GPa, and fully recover upon the removal of the load (Inset in top left). The stress-strain curves are non-linear, outline fully reversible reproducible closed loops whose size and shape depend on grain size, but not strain rate. In one case, a sample was cycled 100 times at 700 MPa, with no apparent changes in the shapes or areas of the loops. This hitherto unreported phenomenon – best described as *fully reversible plasticity* - is attributed to the formation and annihilation of kink bands, defined to be thin plates of shear material bounded by opposite walls of dislocations.

Stress-strain curves for fine and coarse-grained Ti_3SiC_2, Al_2O_3 and Al. Dotted line is linear elastic response expected from Ti_3SiC_2 had kinking *not* occurred. The loop labeled coarse-grained Ti_3SiC_2 represents three loading and unloading cycles that differed from each other by a factor of 10 in loading and unloading rates. The reproducibility is noteworthy. Inset show successive loops obtained as the stress was increased up to 1 GPa. Note all loading curves are identical. Tests were performed on cylindrical specimens (9.8 mm in diameter, 31 mm long). Tests were carried out in air using an MTS810 testing machine in load control mode; the strain was measured by an axial extensometer (25 mm gauge length). In order to maintain sample alignment, the minimum stress in all tests was about 1~3 MPa, at both room and high temperatures.

Based on the results shown in this figure it is fair to label Ti_3SiC_2, and by extension the other MAX phases, a ceramic rubber. We believe the absolute value of the energy loss ($\approx$ 1MJ/m^3) measured at 1 GPa, is a *record* for crystalline solids. The ramifications of having a lightweight cheap, elastically stiff solid, (with a specific stiffness almost 3 times that of Ti) that can be machined with a manual hack saw, with compressive strengths of $\approx$ 1 GPa, that can also damp a significant portion (25 % at 1 GPa) of the mechanical energy will not be inconsequential in applications and fields as diverse as precision machine tools, ultra quiet, vibration free machinery and transportation equipment, industrial robots, the performance of electronic and MEMS devices, the wobble of hard disc drives or low density armor, among others. The further prospect of exploring the more than 50 MAX phases that exist, and the innumerable combinations of solid solutions, is a wonderful one indeed, and one that should prove to be of immense technological and scientific importance and benefit.

Top Right: Typical field-emission scanning electron microscope image of a bridged crack in the coarse-grained Ti3SiC2 microstructure. Heavily deformed lamella bridge the crack, and significant amounts of delamination and bending are observed. Such processes are highly unusual in ceramic systems and may, at least partially, account for the extremely high plateau fracture toughnesses (16 MP√m). The same pattern of ligament formation can be seen in wood that also renders freshly cut wood quite tough.

Bottom right: The July-Aug. 2001feature article and cover of American Scientist were devoted to the MAX phases.

Bottom Left and center: These micrographs are evidence for another new phenomenon in nature; namely self extrusion of Ga and In from porous preforms containing these elements. The whiskers shown (center) grow at room temperature and are solid at all times. They grow as human hair does, from the root. The micrograph on the bottom left shows the same process but at a temperature slightly above the melting point of In. We had previously shown this phenomenon for Ga; this is the first time it has been shown to occur for other elements as well. The practical implications